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Design and Characterization of an Isokinetic Sampling Train for Particle Size Measurements Using Emission Gas Recycle

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16. ABSTRACT The paper describes a particulate sampling train that satisfies the conflicting requirements of isokinetic sample extraction and constant flow rate through an inertial sizing device. A variable fraction of the filtered emission gas is added to the sample upstream of the inertial sizing device to maintain a preselected flow rate through the device, while the gas flow rate into the sampling nozzle is adjusted to remain isokinetic with the local duct velocity. The prototype emission gas recycle (EGR) train was constructed by relatively simple modifications of a commercially available Method 5 sampling system, and much of the sampling technique is identical with Method 5 protocol. The train was tested by comparing parallel runs in the EPA/SoRI wind tunnel using redispersed fly ash. In one series of runs performed without inertial sizing devices, the EGR train and a colocated non-EGR train sampled three-point traverses. The differences of the average mass concentrations measured by the two trains was 3.3%, with a standard deviation of 4.7%. In the next series of runs, identical cyclone inertial sizing devices were added to each train. The difference of the average mass concentration for these runs was 1.2%, with a standard deviation of 5.7%.

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Design and Characterization of an Isokinetic Sampling Train for Particle Size Measurements Using Emission Gas Recycle

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A particulate sampling train has been constructed which satisfies the conflicting requirements of isokinetic sample extraction and constant flow rate through an inertial sizing device. Its design allows a variable fraction of the filtered emission gas to be added to the sample upstream of the inertial sizing device in order to maintain a preselected flow rate through this device while the gas flow rate into the sampling nozzle is adjusted to remain isokinetic with the local duct velocity. The prototype emission gas recycle (EGR) train was constructed by relatively simple modifications of a commercially available Method 5 sampling system, and much of the sampling technique is identical with Method 5 protocol. The train was tested by comparison of parallel runs in the EPA/SRI wind tunnel using redispersed fly ash. In one series of runs performed without inertial sizing devices, the EGR train and a colocated non-EGR train sampled 3-point traverses. The differences of the average mass concentrations measured by the two trains was 3.3 percent, with a standard deviation of 4.7 percent. In the next series of runs, identical cyclone inertial sizing devices were added to each train. The difference of the average mass concentration for these runs was 1.2 percent, with a standard deviation of 5.7 percent.

In order to obtain a representative sample of particulate matter from a flowing gas stream, the sample must be withdrawn isokinetically; that is, the gas flow rate of the sample must be adjusted so that the velocity in the sampling nozzle equals that in the surrounding gas stream. If a velocity mismatch occurs at the nozzle, the particulate matter in the sample gas will be selectively enriched or depleted, leading to an erroneous measurement of particulate concentration. In recognition of this bias, EPA Reference Method 5 and other sampling techniques for ducted particulate emissions specify isokinetic sampling at a grid of points. In order to obtain a representative sample of the average duct concentration, the duct is divided into a number of equal area segments. The centroid of each segment is then sampled for a fixed time interval at sample flow rate isokinetic with respect to the local gas stream velocity.

The procedure outlined above is satisfactory for total particulate mass measurements. However, when sampling with inertial particulate sizing devices such as cascade impactors or sampling cyclones, an additional constraint is introduced. These samplers must be operated at constant flow rate in order to maintain constant size cuts for each particle size fraction. With a fixed nozzle size, it is impossible with conventional sampling trains to satisfy both the requirements of constant sampler flow rate and isokinetic nozzle velocity. Historically, the choice has been made to sample at the fixed flow rate which produces a nozzle velocity equal to the mean stack velocity as determined by EPA Reference Method 2. This choice avoids errors introduced by varying internal flow rates, but introduces errors caused by nonisokinetic sampling over the traverse. If it becomes necessary to measure source emissions of particulate matter less than a specified aerodynamic size (such as PM_{10} emissions) in compliance or enforcement testing, a sampling train must at the same time be accurate in size fractionation and free from anisokinetic sampling bias.

Several alternate sampling train design approaches have been considered that allow isokinetic sampling over a full duct traverse while maintaining a constant flow rate through an inertial sizing device.[1,2,3] These include such concepts as variable area nozzles, split stream sampling probes, probe shroud extractive sampling, and gas recycle concepts. Several of these concepts, including emission gas recycle (EGR), were proposed as modifications to the EPA Source Assessment Sampling System (SASS) to allow isokinetic sampling traverses with this fixed flow rate sampling train.[2]

The EGR concept was subsequently developed into a prototype sampling train,[4] and some testing was performed both at the EPA facilities at Research Triangle Park and under contract by Southern Research Institute. The sampling train uses the principle of emission gas recycle. Its design allows a variable fraction of the conditioned and filtered exhaust gas to be added to the sample between the sample nozzle and the inertial sampler. This allows a preselected constant flow rate through the inertial sampler while the gas flow rate into the sampling nozzle is adjusted to remain isokinetic with the local duct velocity.

The prototype train was constructed by modifications of a commercially available EPA Reference Method 5 sampling system, and much of the sampling technique is identical with Method 5 protocol. It is adaptable to a variety of inertial sizing devices. In this manuscript we will explain the emission gas recycle principle of operation, describe the prototype train, and present the results of parallel testing

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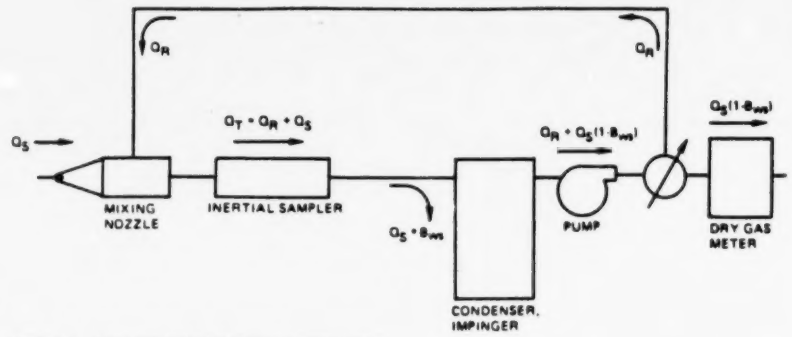


Figure 1. Gas flow in emission gas recycle train.

with the prototype and a conventional isokinetic sampling train.

Principle of Operation

The principle of operation of the EGR train is illustrated in Figure 1. Stack gas is extracted isokinetically at volumetric flow rate Q_s. If the stack moisture fraction is B_{ws}, the sample flow consists of $B_{ws}Q_s$ moisture and $Q_s(1 - B_{ws})$ dry gas flow. At the mixing point a flow, Q_r, of dry recycle gas is added to the sample stream to bring the total flow rate to the predetermined constant level, Q_t. In the impingers or condenser, the moisture content $B_{ws}Q_s$ is removed. After the pump and total flow metering element, the recycle flow Q_r is diverted by means of an adjustable valve. By mass balance, in a leak-free system, the remaining flow which passes the dry gas meter and orifice will simply be $Q_s(1 - B_{ws})$, exactly as would occur in an isokinetic sampling train without gas recycle.

There are several practical requirements for a functional EGR sampling system. The operator must be able to monitor and control accurately two flow rates rather than one. Setup and operation of the train must be simple, and the train must function reliably in normal field sampling environments. The recycle gas mixing must not cause significant particle deposition, must not perturb the cutpoints of the inertial sizing device, and must not introduce artifact particulate matter.

In order to meet these constraints, the prototype train presented in this paper was constructed by modifications to the control module and sampling hardware of a commercially available Method 5 sampling train. Laminar flow elements are used to monitor the recycle and total flow rates. In order to minimize particulate losses, the recycle gas is introduced coaxially in an annulus around the sample gas.

A block diagram of the train is shown in Figure 2. The gas sample which contains particulate matter enters through the sample inlet of the mixing nozzle. After the particulate sample is collected on the inertial sizing device and final sample filter, the gas passes through an impinger train or ice-cooled condenser, followed by a sealed pump controlled by valves V_1 and V_2 for coarse and fine flow adjustment, respectively. From this point, the gas in a standard isokinetic sampling train would pass directly to the dry gas meter and sample orifice and finally be exhausted. In the train as modified for emission gas recycle the gas passes through additional filters and flow metering devices, then through a branch in the sample line which allows the variable fraction of the gas to be reheated and recycled to the annular mixing nozzle. The individual components of the modified train are described below.

A sealed, oil-lubricated pump is typically used in standard control boxes. Our measurements indicate that a small amount of oil droplets escape the oil filter immediately downstream of the pump. This oil mist is not a problem for Method 5 particulate sampling, since all sample collection surfaces are upstream of the pump. However, in the emission gas recycle train this oil mist would be recycled into the sample. To eliminate oil mist carry-over, a leakless sealed oil-free carbon vane pump was installed in place of the standard pump. In addition, an absolute filter was added to the system. After the gas exits this second filter, the total flow is measured using a laminar flow element (LFE, Meriam Model 50MJ10-1/2 Type 10). The gas stream is then split into the recycle and sample flow lines. The sample flow is monitored in the normal manner using a dry gas meter and a calibrated orifice. The recycle gas flow rate is measured using a second LFE (Meriam Model 50MJ10-1/2 Type 11). The recycle gas flow is con-

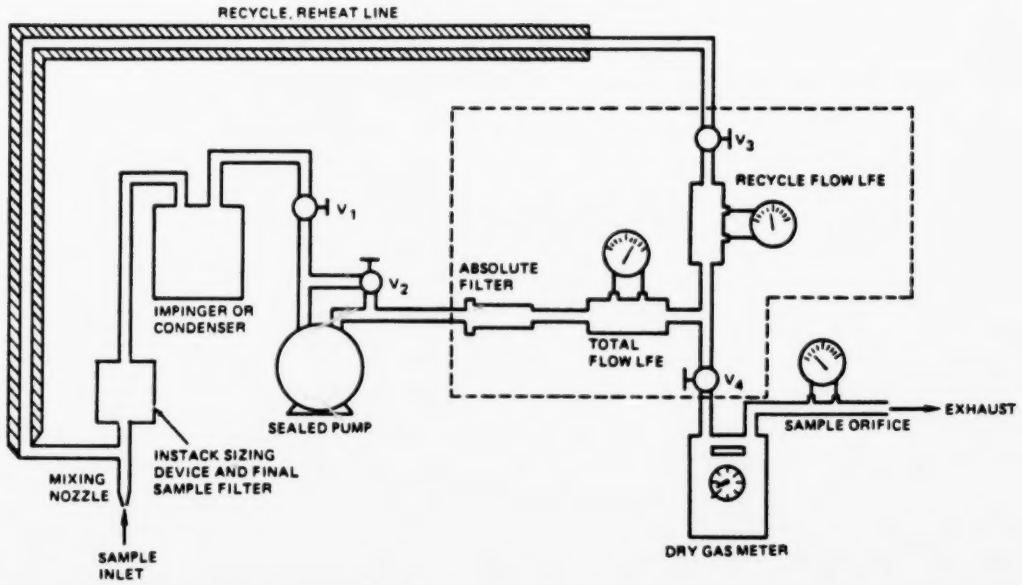
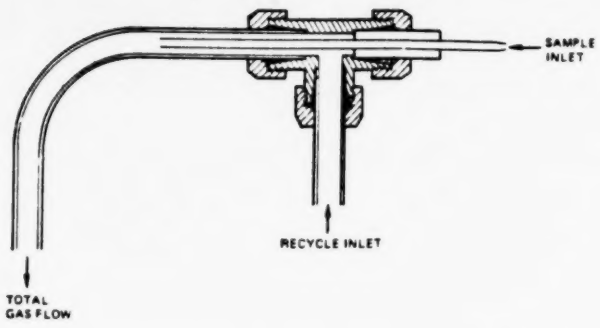


Figure 2. Schematic of the emission gas recycle train.

A. ORIGINAL RESEARCH TRAIN BUTTONHOOK NOZZLE DESIGN



B. MIXING NOZZLE FOR PM_{10} CYCLONE IN PROTOTYPE EGR TRAIN

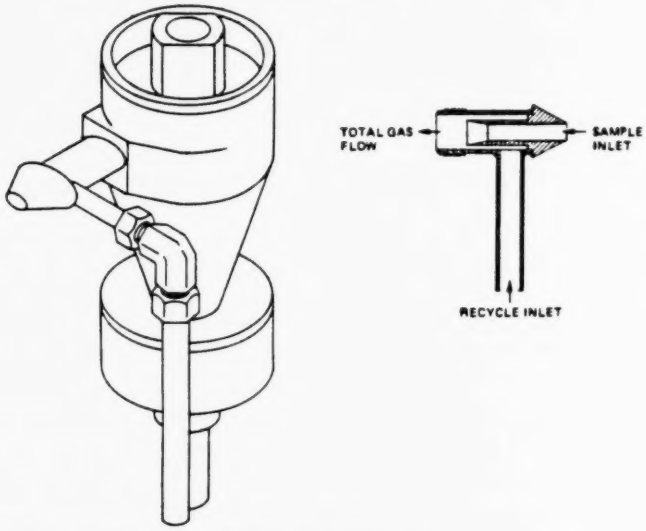


Figure 3. Cross-sectional detail of the EGR mixing nozzles.

trolled by a valve (V_3) located downstream of the LFE (See Figure 2). The recycle gas passes through a heated line within the probe where it is reheated to the duct temperature. Power to the heater is regulated by a proportional temperature controller using a thermocouple sensor on the wall of the recycle line. After heating, the recycle gas passes to the mixing nozzle.

Operation of the emission gas recycle train is similar to standard Method 5 sampling. The sampling flow Q_s (defined as the gas flow rate entering the nozzle) is monitored using the sample orifice and dry gas meter and controlled using valves V_1 and V_2 in the normal manner. Selection of traverse points and sample flow rate are done using standard techniques, such as "slide rule" nomographs. The total dry gas flow $Q_t + Q_s(1 - B_{ws})$ is monitored by using the total flow LFE and controlled using the recycle valve V_3. In practice, the sample and recycle flow settings interact only slightly, so that one or two quick iterations of V_2 and V_3 are needed at a new traverse point. Valve V_4 was added to the system to extend the range of control to higher recycle percentages by adding back pressure to the sample flow line. V_4 needs adjustment only once before a sample run to insure that the maximum necessary recycle flow can be attained.

The mixing nozzle of the original research train is shown in cross-sectional detail in Figure 3A. A stainless steel, ½-inch, union tee is used for the body of the mixing nozzle. The recycle gas enters the nozzle through the "branch" portion of the tee and passes along the annular region outside the sample tube. The sample portion of the nozzle consists of a teflon plug bored to allow a ¼-inch stainless steel tube to be inserted into the tee. The in-stack end of the tube has been ground down to form a 3/16-inch sharp-edged nozzle. As shown in Figure 3A, the nozzle tube extends well back into the mixing nozzle, allowing the recycle flow to fill the annulus as uniformly as possible. The success of measurements with the prototype annular mixing nozzle led to adaptation of this basic design for use on inertial sizing devices. Figure 3B shows an annular mixing nozzle designed for recycle use with Cyclone SRI-I. The dimensions of this nozzle allow the sampler to be inserted into a 4-inch sampling port.

Parallel Testing of Emission Gas Recycle and Conventional Sampling Trains

In order to assess the performance of the prototype EGR train, simultaneous parallel tests were conducted at the wind tunnel facility at Southern Research Institute. The first test series was performed without an inertial sizing device on the sampling trains. A dual sampling probe with a single pitot allowed the EGR train and a second isokinetic sampling train to operate side-by-side in the same test port of the wind tunnel. The EGR sampler was fitted with the 3/16-inch mixing nozzle shown in Figure 3A. The second sampler used a nozzle of similar geometry but without the "tee" inlet for recycle gas entry. Both trains simultaneously sampled fly ash redispersed with a sandblaster dust injector upstream of the wind tunnel test section.

In order to verify equivalent performance of the two trains under the same conditions, the first tests were performed without recycle gas, with both trains sampling isokinetically at a single duct velocity of 43 ft/s (13.1 m/s). A second series of runs was performed using the same hardware in a simulated, three point, isokinetic traverse. In order to simulate a duct traverse, each sampling run was divided into three equal periods in which the wind tunnel was operated at velocities of 51, 43, and 33 ft/s (15.4, 13.0, and 9.9 m/s), respectively. Both samplers were operated at flow rates which were isokinetic with respect to the duct velocity during each sampling period. The EGR train recycle flow was adjusted so that the total flow through the filter was constant (approximately 0.6 actual ft^3/min, or 17 L/min) during the course of each simulated three-point traverse. The positions of the two sampling nozzles on the dual probe holder were reversed between runs.

The results of the sampling runs are shown in Table I. As can be seen, the collection characteristics of the EGR sampling nozzle are unaffected by the recycle of up to 35 percent of the total flow. Furthermore, nozzle losses in the EGR train were consistently lower than in the non-recycle train, suggesting that nozzle losses may not be a problem in the final field sampling train.

The final series of tests incorporated inertial sizing devices into both the re-

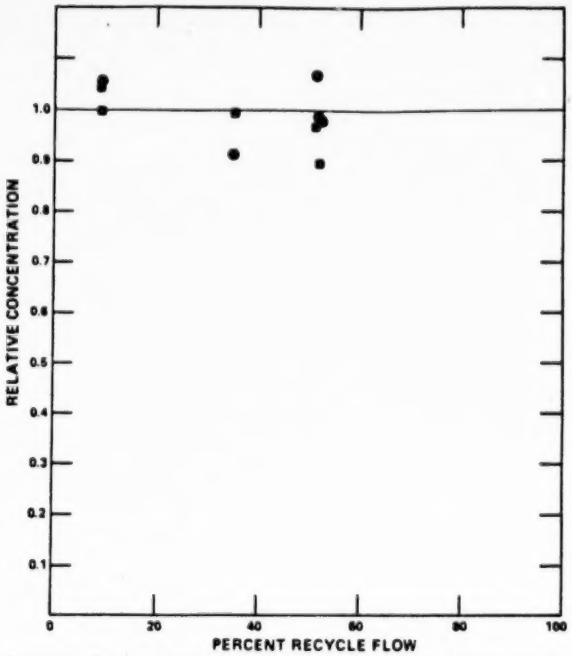


Figure 4. Ratio of particulate concentration measured by EGR cyclone train to parallel cyclone train without recycle. The different symbols distinguish runs made with the two alternate locations of the sample probes.

cycle and non-recycle trains. For this purpose a dual cyclone train consisting of Cyclones I and IV of the EPA/SRI five-stage cyclone sampler[5] was used with each train. Both trains were operated isokinetically with identical cyclone flow rates. Run conditions were varied to test comparability of the two trains at different EGR recycle fractions. For all runs, the $^3/_{16}$-inch EGR mixing nozzle of the geometry shown in Figure 3B was used in the EGR train. Three different nozzles with nominal diameters of 5, 6, and 7 mm were used in the non-recycle train. As both trains sampled isokinetically from points having the same duct velocity, recycle fractions of 9, 36, and 52 percent, respectively, were added to the emission gas recycle sample flow in order to obtain equal cyclone flow rates in both trains. The positions of the two sampling trains were reversed on alternate sampling runs in order to eliminate systematic differences due to particle stratification in the wind tunnel duct. No evidence of stratification effects was noted. Several runs were made for each recycle fraction. In all but the last run, the wind tunnel velocity was adjusted so that the cyclone flow rate in both trains was approximately 0.6 ft^3/min (17 L/min).

The results of the cyclone tests are contained in Table II. As indicated by the mean percent difference and standard deviation values shown in Table I and II, the mass concentrations measured with the paired recycle and non-recycle trains agree within the expected experimental error. The ratio of the concentrations measured with the EGR train to those measured with the non-recycle train are shown in Figure 4. In the figure, the two relative positions of the sampling trains are denoted by different symbols. As can be seen, the ratio shows no obvious dependence on recycle fraction or on the relative position of the probes. The particulate fractions collected by the initial cyclones in the parallel trains are likewise comparable in magnitude. There is a possible bias toward lower fractional collection in the emission gas recycle cyclone, but this difference appears to be significant in only one run.

Conclusions

The prototype EGR sampling train used for these studies has proven to be easy to adjust and operate, involves very little change from the sampling protocol used in EPA Reference Method 5, and can be duplicated at modest cost using commercially available components. The results of the parallel testing to date show that measured

Table I. Results of parallel tests with EGR and EPA Reference Method 17 trains using buttonhook nozzles and in-stack filters.

Sample train	Sample flow (acfm)	Percent recycle flow	Percent isokinetic	Nozzle deposit, percent	Mass loading (mg/dsm^3)	Difference, percent
			Single flow runs without recycle			
EGR	0.5146	0.0	104.5	17.51	493.4	−4.1
M-17	0.5154	—	105.0	52.4	514.7	
EGR	0.4849	0.0	98.5	15.08	539.9	−0.1
M-17	0.5144	—	104.8	21.09	540.4	
EGR	0.4875	0.0	98.5	9.51	534.1	−3.9
M-17	0.5144	—	104.2	15.22	555.8	
				Mean percent difference		−2.7
				Standard deviation		2.3
			Stimulated three-point traverses			
EGR	0.6648	0.0	114.7			
M-17	0.7205	—	124.7			
EGR	0.4810	16.1	98.6			
M-17	0.5047	—	103.8			
EGR	0.3694	34.2	99.1			
M-17	0.4126	—	111.1			
EGR (avg)	0.5046	16.1	103.5	4.68	558.8	3.6
M-17 (avg)	0.5441	—	112.0	8.76	539.6	
EGR	0.5605	0.0	96.5			
M-17	0.6298	—	108.8			
EGR	0.4897	17.0	100.2			
M-17	0.5137	—	105.4			
EGR	0.3743	35.5	100.2			
M-17	0.4052	—	108.9			
EGR (avg)	0.4748	17.5	97.2	5.65	762.8	7.8
M-17 (avg)	0.5152	—	105.8	8.88	707.5	
EGR	0.5716	0.0	98.7			
M-17	0.5774	—	100.1			
EGR	0.4860	15.5	99.7			
M-17	0.5045	—	103.8			
EGR	0.3832	35.5	102.7			
M-17	0.397[illegible]	—	107.0			
EGR (avg)	0.480[illegible]	16.6	98.5	5.42	898.0	−1.6
M-17 (avg)	0.4925	—	101.4	13.31	912.9	
				Mean percent difference		3.3
				Standard deviation		4.7

Table II. Results of parallel tests using dual cyclone trains (Cyclones I and IV) with EGR nozzle and with standard (STD) non-recycle configuration.

Sample train	Sample flow (acfm)	Percent recycle flow	Percent isokinetic	Mass loading (mg/dsm^3)	Difference, percent	Cyclone I catch, percent
EGR	0.5157	9.3	95.8	219.0	−0.3	66.9
STD	0.6020	—	101.8	219.5		68.9
EGR	0.5246	9.2	96.6	275.3	5.5	67.7
STD	0.6187	—	103.6	261.0		70.5
EGR	0.5302	9.1	97.1	277.1	4.3	61.9
STD	0.6168	—	102.8	265.8		70.4
EGR	0.3733	35.7	98.8	337.3	−8.9	63.6
STD	0.6150	—	102.9	370.3		67.5
EGR	0.3782	35.3	99.5	345.4	−0.4	64.2
STD	0.6219	—	103.4	346.7		70.5
EGR	0.2806	51.5	102.3	502.1	6.2	49.2
STD	0.5903	—	99.9	472.7		68.3
EGR	0.2692	52.0	99.3	1591.5	−1.5	80.8
STD	0.5949	—	101.9	1615.1		82.9
EGR	0.2763	52.2	101.9	638.0	−11.0	88.1
STD	0.5970	—	102.3	716.7		88.2
EGR	0.2771	52.9	99.2	882.8	−2.4	75.2
STD	0.6199	—	103.0	904.4		78.8
EGR	0.455	51.4	97.5	772.9	−3.8	87.4
STD	1.0365	—	105.3	803.1		88.7
				Mean percent difference	−1.2	
				Standard deviation	5.7	

particulate concentrations while operating under recycle conditions compare well to those of isokinetic samples without recycle.

The ability to maintain constant total gas flow rate while sampling isokinetically will allow the incorporation of the exhaust gas recycle methodology into inertial particle sizing trains. Using emission gas recycle with these devices, we may hope to measure size specific emission factors with accuracy comparable to that obtained by Methods 5 and 17.

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